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An energy-efficient MAC protocol based on IEEE 802.11 in wireless ad hoc networks

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Abstract Energy efficiency is a measure of the performance of IEEE 802.11 wireless multihop ad hoc networks. The IEEE 802.11 standard, currently used in wireless multihop ad hoc networks, wastes bandwidth capacity and energy resources because of many collisions. Therefore, controlling the contention window size at a given node will increase not only the operating life of the battery but also the overall system capacity. It is essential to develop effective backoff schemes for saving power in IEEE 802.11 wireless multihop ad hoc networks. In this paper, we propose an energy-efficient backoff scheme and evaluate its performance in an ad hoc network. Our contention window mechanism devised by us grants a node access to a channel on the basis of the node's percentage of residual energy. We use both an analytical model and simulation experiments to evaluate the effective performance of our scheme in an ad hoc network. Our extensive ns-2-based simulation results have shown that the proposed scheme provides excellent performance in terms of energy goodput, end-to-end goodput, and packet delivery ratio, as well as the end-to-end delay.

Keywords IEEE 802.11 · Contention window mechanism · Ad hoc networks · ns-2 · Energy goodput

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1 Introduction

There has been a growing interest in mobile wireless networks in recent years. Such networks are formed by mobile hosts (or nodes, users) that do not have direct links to all other hosts. They can be rapidly deployed without any established infrastructure or centralized administration; in this situation, they are called ad hoc networks [1]. Because of the greater affordability of commercial radios, ad hoc networks are likely to play an important role in computer communications. The applications of ad hoc network are in building, campus, battlefield, or rescue environments.

Unlike wired networks, problems such as: mobility of nodes, shared broadcast channel, hidden and exposed terminal problem, and constraints on resources, such as bandwidth and battery power, limit the applications of ad hoc networks. Due to the above-mentioned factors, providing energy awareness, packet delivery ratio, and end-to-end goodput guarantees in ad hoc networks are some tough propositions.

Packet scheduling in the medium access control (MAC) layer is for choosing the next packet to transmit, such that a real attempt is made to satisfy the end-to-end delay and packet delivery ratio guarantees. Wireless scheduling algorithms significantly differ from their corresponding wired networks. In a wired network, when a node has data packets for transmission, collisions may be occur only for the packets in its own transmission queue. But in ad hoc networks, the channel is broadcast; multiple nodes may contend for the channel simultaneously, resulting in higher probability of transmission errors than wired networks. To avoid the collision problem, a node must be aware of traffic at nodes in its two-hop contention area [2]. Therefore, an efficient backoff algorithm is an important issue for packet scheduling in ad hoc networks.

Recently, the renewed interests in ad hoc networks have centered on using the IEEE 802.11 MAC mechanism. In ref. [3], the authors raised the question: Can the IEEE 802.11 work well in wireless ad hoc networks? They concluded that the protocol was not designed for multihop networks. Although IEEE 802.11 MAC can support some ad hoc network architecture, it is not intended to support the wireless multihop mobile ad hoc networks, in which connectivity is one of the most prominent features.

The performance of the IEEE 802.11 MAC mechanism is determined by backoff scheme, request-to-send/clear-to-send (RTS/CTS) mechanism, transmission range, etc. In addition, whether or not the IEEE 802.11 MAC protocol is efficient will affect the performance of ad hoc networks. The metrics for the performance of 802.11 ad hoc networks may have throughput, delay, jitter, energy dissipation, etc.

A simulation analysis of the backoff mechanism in the IEEE 802.11 standard has been presented in ref. [4]. Since the backoff and contention window are closely related, the selection of the contention window will affect the network throughput. The authors in ref. [4] showed the effective throughput and the mean packet delay versus offered load for different values of the contention window parameter and the number of contending stations.

The throughput and the mean frame delay, as functions of offered load for different RTS threshold values and numbers of stations transmitting frames of random sizes, are presented in ref. [5]. When the number of stations increases, the RTS threshold should be decrease. While transmitting frames of random sizes, it is recommended to always set the RTS/CTS mechanism independent of the number of contending stations. The absence of a RTS/CTS mechanism entails considerable network performance degradation, especially for large values of offered load and numbers of contending stations [5]. The dependence between the maximum throughput and the RTS/CTS threshold parameter for different mean lengths of frames was studied in ref. [6].

The influence of packet size on the network throughput has been discussed in ref. [7]. When the load is fixed and the packet size is increased, the contending numbers will be decreased and the network performance will be degraded. If the hidden terminal problem occurs, the performance worsens. When the network load is not heavy, the network performance varies slightly as the packet size changes. When the network load is heavy, the hidden terminal problem worsens and the network performance is lowered for the longer packet size.

Under a wide set of network and load conditions, multihop networks have lower performance than do single hop networks [8]. Data throughput is maximized when all nodes are in range of each other. The performance degradation in networks may be explained by the fact that channel contention in mobile ad hoc networks based on the 802.11 standard is not ideal.

A new backoff algorithm is proposed in ref. [9], and the authors model it with a Markov chain; its saturation throughput is measured under several conditions and several sets of parameters which are to be adjusted according to the network condition, with the aim of approaching maximum throughput when the stations are saturated.

In ref. [10], the author proposed a Markov chain to model the IEEE 802.11 distributed coordination function (DCF). This Markov chain model analysis applies to both packet transmission schemes employed by DCF; for the model, the author proposed an extensive throughput performance evaluation of basic and RTS/CTS access mechanisms.

In ref. [11], the author proposed an enhanced distributed channel access (EDCA) mechanism under saturation condition and analyzed the throughput and delay performance of EDCA.

In this paper, we are interested in energy goodput, where the energy goodput is the number of packets delivered successfully per unit energy. The objective is to save the energy consumption and improve the system throughput when network data traffic may change frequently in an unpredictable way. We present the results of a simulation study that characterizes the energy goodput, energy dissipation per packet, energy dissipation per hop, packet delivery ratio, end-to-end goodput and end-to-end delay of ad hoc networks. In particular, we use the constant bit rate (CBR) connection numbers as the main varying parameters for the above mentioned performance metrics. If the backoff scheme does not consider the residual energy, this may cause some nodes to have shorter life times than other nodes will. This situation will affect the establishment of a route and degrade the performance of the entire network. In order to increase throughput and save power, if a node has lower residual energy, the node should have smaller backoff time to transmit its packets. On the other hand, if a node has higher residual energy, the node should have larger backoff time. Therefore, we redefined the backoff mechanism in IEEE 802.11 DCF as an energy-efficient backoff scheme.

2 Contention window control scheme

2.1 IEEE 802.11

IEEE 802.11 is a standard for wireless ad hoc networks and infrastructure LANs [12] and is widely used in many testbeds and simulations in wireless ad hoc networks researches. IEEE 802.11 MAC layer has two medium access control methods: the DCF for asynchronous contention-based access, and the point coordination function for centralized contention-free access. In this paper, we consider the IEEE 802.11 DCF MAC protocol as the medium access control protocol in wireless ad hoc networks.

The DCF access scheme is based on a carrier sense multiple access with collision avoidance (CSMA/CA) protocol [13]. Before initiating a transmission, a station senses the channel to determine whether another station is transmitting. If the medium is found to be idle for an interval that exceeds the distributed inter-frame space (DIFS), the station starts its transmission. Otherwise, if the medium is busy, the station continues monitoring the channel until it is found idle for a DIFS. A random backoff interval is then selected and used to initialize the backoff timer. This timer is decreased as long as the channel is sensed idle, stopped when a transmission is detected and reactivated when the channel is idle again for more than a DIFS. When a receiver receives a successful data frame then it sends an acknowledgement frame (ACK) after a time interval called a short inter-frame space (SIFS) to the sender.

An optional four way hand-shaking technique, known as the request-to-send/clear-to-send (RTS/CTS) mechanism is also defined for the DCF scheme [14]. Before transmitting a packet, a station operating in the RTS/CTS mode "reserves" the channel by sending a special RTS short frame. The destination station acknowledges the receipt of an RTS frame by sending back a CTS frame, after which normal packet transmission and ACK response occurs. Since collision may occur only on the RTS frame, and it is detected by the lack of CTS response, the RTS/CTS mechanism allows to increase the system performance by reducing the duration of a collision when long messages are transmitted. The RTS/CTS is designed to combat the hidden terminal problem.

Contention window control scheme is a well-known method for resolving contentions between different stations willing to access the medium. The method requires each station to choose a random number between 0 and a given number, and wait for this number of slots before accessing the medium, while always checking whether a different station accessed the medium before. The slot time is defined in such a way that a station will always be capable of determining if any other station has accessed the medium at the beginning of the previous slot; this reduces the collision probability by half [15]. Exponential backoff means that each time the station chooses a slot and happens to collide with others, this will exponentially increase the maximum number for the random selection. The integer number of backoff time slots is uniformly drawn in a defined interval called the contention window.

The algorithm used by 802.11 to make this contention window evolve is called binary exponential backoff (BEB). After each successful transmission, the contention window is set to [0, contention window $(\mathrm{CW})_{\min} - 1$] (its initial value). When node successive collisions occur, the contention window is set to $[0, \min(1{,}024, 2^i * \mathrm{CW}_{\min} - 1)]$; i is the number of retransmission; if $i > 7$, the contention window is reset to its initial value. It is the retry limit of the BEB algorithm [15].

The following equation is the backoff mechanism for IEEE 802.11.

$$\mathrm{Backoff} = \mathrm{INT}(\mathrm{CW} * \mathrm{Random}()) * \mathrm{SlotTime} \quad (1)$$

SlotTime can roughly be considered as the quantum of time in WLANs and is dependent on the characteristic of stations in the specific independent basic service set [9]. Random() is a random real number over the interval [0,1]. CW is an integer chosen from an increasing series of integers. The first integer in this series is $\mathrm{CW}_{\min}$ and the last one is $\mathrm{CW}_{\max}$. Both these values are specified in the stations according to the physical layer and MAC technique characteristics. One important thing is that the Random() generated in each station should be statistically independent of Random() in other stations [9].

2.2 Minooei 802.11

In ref. [9], the authors proposed a Minooei 802.11 (M802.11) backoff algorithm and modeled it with a discrete-time Markov chain. The authors suggested choosing CW from the intervals:

$$\left[\mathrm{CW}_{i-1}, \mathrm{CW}_i\right], i = 1, 2, ..., m \quad (2)$$

$$\left[1, \mathrm{CW}_0\right], i = 0 \quad (3)$$

where CW_i is the contention window of the ith backoff stage (ith backoff stage means the station has collided i times so far), and with the condition of the distances between the CW_i's strictly increasingly (like when $\mathrm{CW}_i = 2^i * \mathrm{CW}_{\min} - 1$). When a frame has collided i times, with increasing i the contending stations which are at the same stage as the station under consideration, are too many and the range of choosing CW∗Random() should become larger; this is accomplished by having the above mentioned condition and by having this lower boundary for CW∗Random() in M802.11. In this way, the contending stations are also classified according to their backoff stages. The advantage of this method is classification of the stations by just incrementing the range of backoff times for a fixed number of stations.

M802.11 decrements the backoff counter by just one unit instead of resetting CW to $\mathrm{CW}_{\min}$. M802.11 just reached a backoff stage which is optimal for traffic at that period of time, so it is better not to lose the frame and it seems that in this way delays will also decrease.

The following equation is the backoff mechanism for M802.11.

$$\mathrm{Backoff} = \mathrm{Uniform}\left[\left(2^{i-1} * \mathrm{CW}_{\min} - 1\right), \left(2^i * \mathrm{CW}_{\min} - 1\right)\right] * \mathrm{SlotTime} \quad (4)$$

2.3 Energy-efficient 802.11(E802.11)

The objective of the energy-efficient backoff procedure is to save power and increase the throughput for a node with respect to those nodes in the two-hop contention area of the node. Let i denote the number of retransmission attempts made for a packet, and $i_{\max}$ represent the maximum number of retransmission attempts permitted.

Our proposed energy-efficient backoff mechanism is defined as follows:

$$\mathrm{Backoff} = \mathrm{INT}\left((\mathbf{E}) * \mathrm{CW}_{\min}\right) + \mathrm{Uniform}\left[(2^{i-1} * \mathrm{CW}_{\min} - 1), \left(2^i * \mathrm{CW}_{\min} - 1\right)\right]\right) * \mathrm{SlotTime} \quad (5)$$

where

E is the percentage of residual energy of a node, and Uniform[∗] is the random number generation function with uniform distribution.

If a node had a higher percentage of residual energy in its two-hop contention region, then it will have a higher backoff time according to our energy-efficient backoff mechanism; otherwise, it will have lower backoff time.

3 Analytical model for energy-efficient 802.11

In this paper, Markov chain is used to model the backoff operation of each station. Our scheme is similar to that of [9] and [10]. Let $b(t)$ be the stochastic process representing the backoff time counter for a given station. Let m be the maximum backoff stage. Let $s(t)$ be the stochastic process representing the backoff stage $(0, \ldots, m)$ of the station at time t. Let us adopt the notation $W_i = 2^i \mathrm{CW}_{\min}$, where $i \in (0, m)$ is called "backoff stage.". Thus, the process $\{s(t), b(t)\}$ of our energy-efficient backoff scheme is a Markov chain. Figure 1 shows the Markov chain model with the state transition graph for tracking the status of every station at every slot time. We define the D_i via

$$D_i = \mathrm{INT}(E * \mathrm{CW}_{\min}) + W_{i-1}, i \in (1, m) \quad (6)$$

$$D_{\max} = \mathrm{INT}(E * \mathrm{CW}_{\min}) + W_{m-1} \quad (7)$$

and define

$$D_0 = \mathrm{INT}(E * \mathrm{CW}_{\min}) + (\mathrm{CW}_{\min} - 1), i = 0 \quad (8)$$

3.1 Packet transmission probability

As in ref. [9] and [10], the key approximation in this model is that, at each transmission attempt and regardless of the number of retransmissions suffered, each packet collides with an independent probability p. In Fig. 1, we adopt the short notation used in ref. [9] and [10]. $P\{i_1, k_1\} = P\{s(t+1) = i_1, b(t+1) = k_1 | s(t) = i_0, b(t) = k_0\}$. In this Markov chain, the only non-null one-step transition probabilities are:

$$\begin{cases} P\{i, k|i, k+1\} = 1 & k \in (W_{i-1}, W_i - 2), i \in (0, m) \\ P\{i, k|i-1, 0\} = p/D_i & k \in (W_{i-1}, W_i - 1), i \in (1, m) \\ P\{i-1, k|i, 0\} = (1-p)/D_{i-1} & k \in (W_{i-1}, W_i - 1), i \in (1, m) \\ P\{i, k|i, 0\} = (1-p)/D_m & i = 0, m \end{cases}$$

Let $b_{i,k}$, $i \in (0, m)$, $k \in (W_{i-1}, W_i - 1)$ be the stationary distribution of the Markov chain. Let τ be the

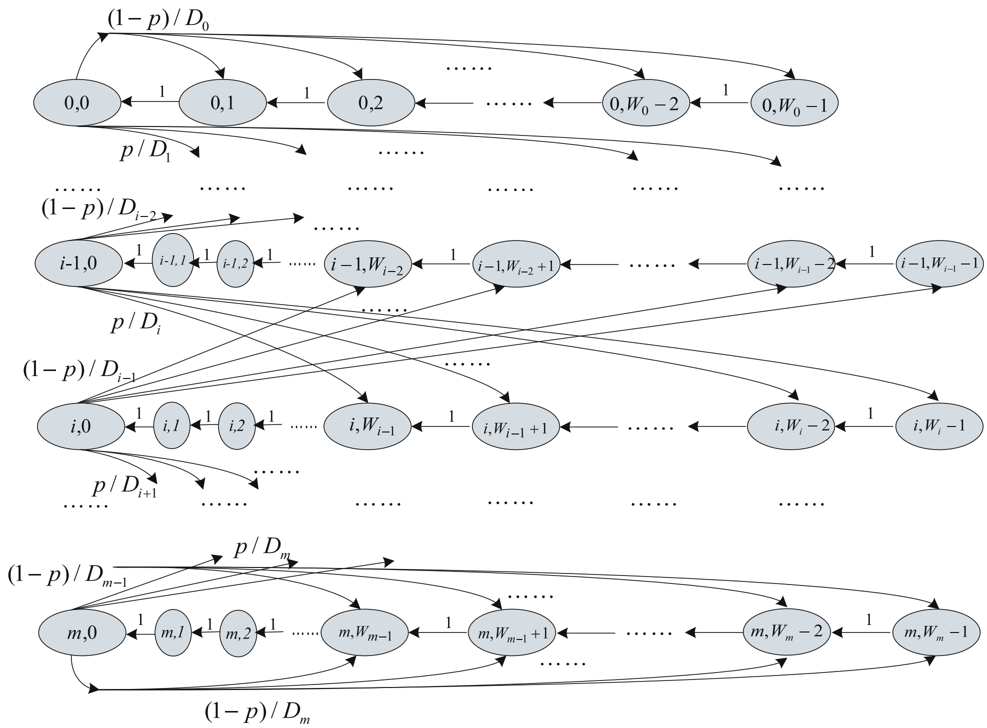

Fig. 1 Markov chain model for the energy-efficient backoff window size scheme

probability that a station transmits in a randomly chosen slot time. Let μ be $\frac{p}{1-p}$. Firstly, note that

$$p \cdot b_{i-1,0} = (1-p) \cdot b_{i,0};\ i \in (0, m) \tag{9}$$

$$b_{i,0} = \frac{p}{1-p} \cdot b_{i-1,0} \tag{10}$$

$$b_{i,0} = \left(\frac{p}{1-p}\right)^{i} b_{0,0} = \mu^{i} b_{0,0} \tag{11}$$

$$b_{m,0} = \left(\frac{p}{1-p}\right)^{m} b_{0,0} = \mu^{m} b_{0,0} \tag{12}$$

Because of the Markov chain regularities, for each $k \in (W_{i-1}, W_i - 1)$, it is

$$b_{i,k} = \frac{D_i - k}{D_i} \cdot \begin{cases} (1-p)b_{0,0} + (1-p)b_{i+1,0} & i = 0 \\ pb_{i-1,0} + (1-p)b_{i+1,0} & i \in (0, m) \\ pb_{i-1,0} + pb_{m,0} & i = m \end{cases}$$

By means of relating Eqs. 11 and 12, $b_{i,k}$ can be simplified as:

$$b_{i,k} = \frac{D_i - k}{D_i} b_{i,0};\quad i \in (0, m), k \in (W_{i-1}, W_i - 1) \tag{13}$$

From Eqs. 11 to 13, all the values $b_{i,k}$ are expressed as functions of the value $b_{0,0}$ and of the conditional collision probability p. Then, $b_{0,0}$ can finally be determined by imposing the normalization condition, simplified as follows:

$$\begin{aligned} 1 &= \sum_{i=0}^{m} \sum_{k=1}^{D_i - 1} b_{i,k} \\ &= \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{D_i - 1} \frac{D_i - k}{D_i} \\ &= \sum_{i=0}^{m} b_{i,0} \frac{D_i + 1}{2} \\ &= \frac{b_{0,0}}{2} \sum_{i=0}^{m} \left(\frac{p}{1-p}\right)^{i} (D_i + 1) \end{aligned}$$

from which

$$b_{0,0} = \frac{2}{\sum_{i=0}^{m} \left(\frac{p}{1-p}\right)^{i} (D_i + 1)} \tag{14}$$

Due to D_i=INT($E * \mathrm{CW}_{\min}$)+W_{i-1}, Then

$$b_{0,0} = \frac{2}{\sum_{i=0}^{m} \left(\frac{p}{1-p}\right)^{i} (\mathrm{INT}(E * \mathrm{CW}_{\min}) + W_{i-1} + 1)} \tag{15}$$

Now the probability τ can be expressed as:

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1-\mu^{m+1}}{1-\mu} b_{0,0} = \frac{(1-p)\left(1-\left(\frac{p}{1-p}\right)^{m+1}\right)}{1-2p} \cdot \frac{2}{\sum_{i=0}^{m}\left(\frac{p}{1-p}\right)^{i}(\mathrm{INT}(E * \mathrm{CW}_{\min}) + W_{i-1} + 1)}$$

In the stationary state, each station transmits a packet with probability τ. So, we get:

$$p = 1 - (1-\tau)^{n-1} \quad (16)$$

3.2 Saturation throughput

Let P_{tr} be the probability that there is at least one transmission in the considered slot time. And let P_s be the probability that a transmission is successful, given the probability P_{tr}. Therefore, we get:

$$p_{\mathrm{tr}} = 1 - (1-\tau)^{n} \quad (17)$$

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{p_{\mathrm{tr}}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^{n}} \quad (18)$$

Now we are able to express the normalized system throughput S as the ratio

$$S = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]} = \frac{P_s P_{\mathrm{tr}} E[P]}{(1-P_{\mathrm{tr}})\sigma + P_{\mathrm{tr}} P_s T_s^{\mathrm{rts}} + P_{\mathrm{tr}}(1-P_s) T_c^{\mathrm{rts}}}$$

Let T_s^{rts} and T_c^{rts} be the average time the channel is sensed busy because of a successful transmission or a collision for the RTS/CTS access scheme. Let $E[P]$ be the average packet length and σ is the duration of an empty slot time. Let the packet header be $H = \mathrm{PHY}_{\mathrm{hdr}} + \mathrm{MAC}_{\mathrm{hdr}}$ and propagation be δ. For the RTS/CTS access scheme, we get:

$$T_s^{\mathrm{rts}} = \mathrm{RTS} + \mathrm{SIFS} + \delta + \mathrm{CTS} + \mathrm{SIFS} + \delta + H + E[P] + \mathrm{SIFS} + \delta + \mathrm{ACK} + \mathrm{DIFS} + \delta$$

$$T_c^{\mathrm{rts}} = \mathrm{RTS} + \mathrm{DIFS} + \delta$$

Saturation throughput for energy-efficient 802.11 is shown in Fig. 2 for the case when the RTS/CTS method is adopted.

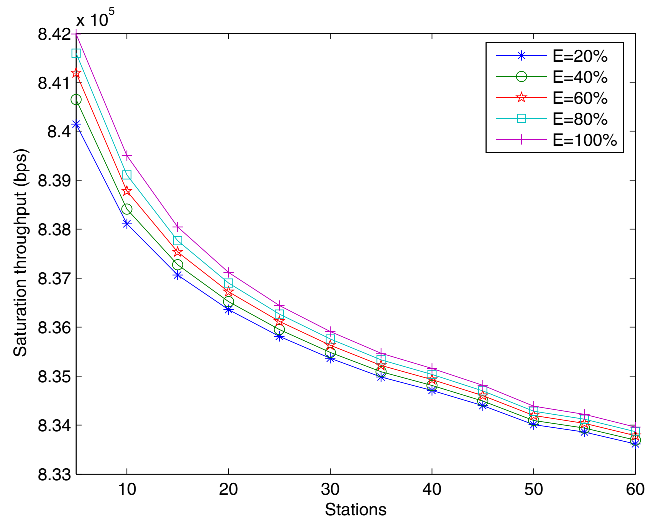

Fig. 2 Saturation throughput for energy-efficient 802.11 analytical model

4 Simulation environment

We used simulations to study the performance of the ad hoc network using the IEEE 802.11 DCF MAC. Results reported in this paper are performed under ns-2 network simulator [16]. In ref. [17], the authors make the 802.11 power saving mechanism applicable in a mobile ad hoc network with dynamic source routing (DSR) and to achieve an additional energy saving by identifying and eliminating unnecessary communication activities. In ref. [18], the authors present a scheme that decreases the risk of a data packet encountering a dead-end situation as it is forwarded to its destination with a 2-Mb/s IEEE 802.11 shared-media radio WaveLAN and CBR traffic pattern. In ref. [18], the authors compare the system performance with existing schemes by adjusting the speed of node mobility, the density of node. In this paper, we focus on the impact of network data traffic to energy consumption and system throughput.

In most simulation runs, we considered 100 nodes randomly distributed over a square area of 670 × 670 m^2, and simulated 150 s of real time. To focus on the power awareness study, we did not consider mobility in this paper and all nodes were assumed to be stationary, in order to eliminate packet loss due to broken routes caused by mobility.

Communications between nodes are modeled using a uniform node-to-node communication pattern with CBR UDP traffic sources sending data in 512-byte packets at a rate of 20 packets/s [19]. Each CBR source corresponds to 94,720 bps bandwidth requirement for data frames (including the 8-byte UDP header, 20-byte

IP header, 24-byte MAC header and 28-byte physical layer header) at the radio channel and 81,920 bps useful data throughput. A total of 5, 10, 15, 20, 25, and 30 CBR connections were generated to represent different levels of loading, with a node being the source of only one connection. All CBR connections were started at times uniformly distributed during the first seconds of simulation and then remained active throughout the entire simulation run. Table 1 lists the simulation parameters in this paper.

Each of our simulation results is the average from five randomly generated network topologies. Furthermore, in order to generate a more uniform topology so that the network will not become disconnected when N (the average number of neighbors) is small, we divided the topology into 25 regions and four nodes were randomly placed in each region. The distances were also uniformly distributed between the source node and the destination node. That is, we made sure that there were roughly equal numbers of short, medium and long connections. An example of the network node distribution is shown in Fig. 3.

In wireless networks, a routing mechanism is needed for the communications between two hosts that are not within wireless transmission range of each other. We chose DSR as the routing protocol in our simulations [20]. Source routing is a routing technique in which the sender of a packet determines the complete sequence of nodes through which to forward the packet; the sender explicitly lists this route in the packet's header, identifying each forwarding "hop" by the address of the next node to which to transmit the packet on its way to the destination host. The sender knows the complete hop-by-hop route to the destination. The protocol consists of two major phases: route discovery and route maintenance. Route discovery allows any host in the ad hoc network to dynamically discover a route to any other host in the ad hoc network, whether directly reachable within wireless transmission range or reachable through one or more intermediate network hops through other hosts. Route maintenance is the mechanism by which a packet's sender detects if the network topology has changed such that it can no longer use its route to the destination because two nodes listed in the route have moved out of range of each other. When route maintenance indicates a source route is broken, the sender is notified with a route error packet. The sender can then use any other route to the destination already in its cache or can invoke route discovery again to find a new route.

Table 1 Simulation parameters

Parameter	Values
Nominal bit-rate	2 Mb/s
Nominal radius	250 m
Number of nodes	100
Square area	670 × 670 m^2
Simulation time	150 s
Packet size	512 byte
Data rate	20 packets/s
CW_{min}	32
CW_{max}	1,024
CBR connections	5, 10, 15, 20, 25, and 30
Energy dissipated for transmit	2 J
Energy dissipated for receive	1 J
Energy dissipated for sleep	0.01 J
Sleep time	1 s
Transition power	0.05 J
Transition time	0.005 s
Initial energy	200 J

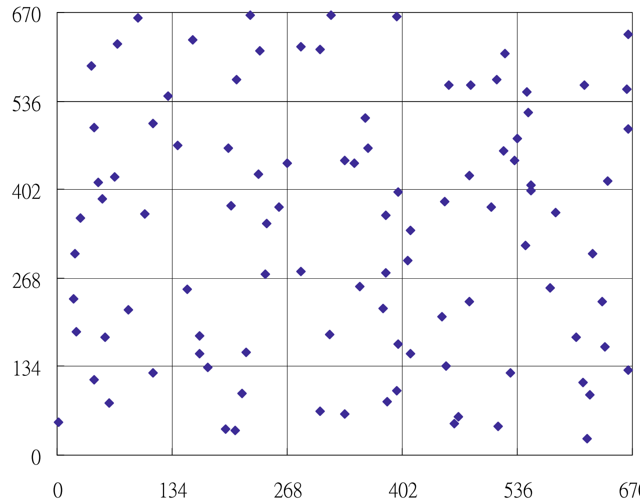

Fig. 3 A sample of nodes' positions

Figure 4 shows the average number of hops for a packet that successfully reached the destination node with a 95% confidence interval vs. the number of connections. We can see that there are roughly equal numbers of hops for 802.11, M802.11, and E802.11 in all cases.

The definition of the network lifetime as the time of the first node failure is a meaningful measure in the sense that a single node failure can make the network become partitioned and further services be interrupted [21]. In ref. [22], the authors show that the choice of this network lifetime leads to a max–min type (bottleneck) optimization problem, because we want to maximize the first node failure (minimum) time. Therefore, we focus on the energy goodput, end-to-end goodput and end-to-end delay. In addition, each node has enough initial energy (200 J) and this means that every node will not die at the expiration time of the simulation in this paper.

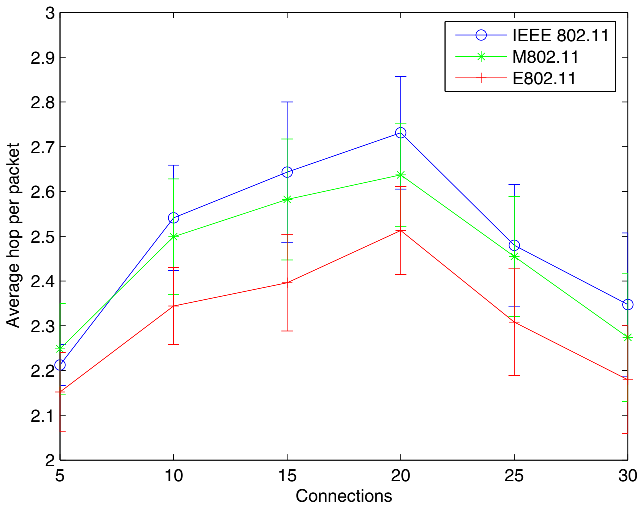

Fig. 4 The average number of hops for a packet that successfully reached the destination node for various number of connections

Energy consumption remains a critical problem in wireless ad hoc networks since battery technology cannot keep up with rising communication expectations. Energy goodput is defined as the ratio of the total bits transmitted to the total energy consumed and reflects the network lifetime. If the energy consumption is higher then the network lifetime reduces. The proliferation of multimedia applications over resource-constrained wireless networks has raised the need for techniques that adapt these multimedia applications both to clients' quality of service (QoS) requirements and to network resource constraints. Therefore, increasing attention is paid to the end-to-end delay analysis of transmissions over error-prone channels. Packet delivery ratio is defined as the number of packet received to the number of packets sent. End-to-end delay and packet delivery ratio is used to evaluate wireless ad hoc networks performance as a means of carriage for time-critical data. End-to-end goodput is the actual bandwidth and is only dependent on packet delivery ratio. Lower packet delivery ratio reflects a larger number of packets being dropped due to link failures or network congestion. Then lower packet delivery ratio will create lower end-to-end goodput and lower fruitful hop-put. In addition, lower packet delivery ratio will create higher end-to-end delay.

Therefore, in order to better understand the characteristics of energy-efficient 802.11 wireless networks in scenarios considered for this paper, we evaluated the performance of 802.11, M802.11, and E802.11 in ad hoc networks based on the following metrics:

- Energy goodput: the number of packets delivered successfully per unit energy;
- End-to-end goodput: the actual bandwidth that is obtained by CBR connections;
- Fruitful hop-put: the numbers of radio transmission (or hops) for data packets that successfully arrive at their final destinations;
- Wasted hop-put: the numbers of radio transmission (or hops) for data packets that cannot successfully arrive at their final destinations;
- Total hop-put: the sum of fruitful hop-put and wasted hop-put; This is an indicator of the *work* produced by the multihop network;
- End-to-end delay per packet: the total delay experienced by a packet that successfully reached the destination node.

5 Performance evaluations

In this section, we evaluate how our proposed energy-efficient backoff mechanism impacts the performance of the wireless ad hoc networks.

5.1 Energy goodput

Figure 5 shows the number of packets delivered successfully per unit energy with a 95% confidence interval vs. the number of connections for 802.11, M802.11, and E802.11.

From Fig. 5, we see that E802.11 has more packets received than 802.11 and M802.11 at the same energy dissipation. The reason is that we consider the node's energy in the backoff scheme; this will decrease the probability of collision in a two-hop contention area and save more energy consumption.

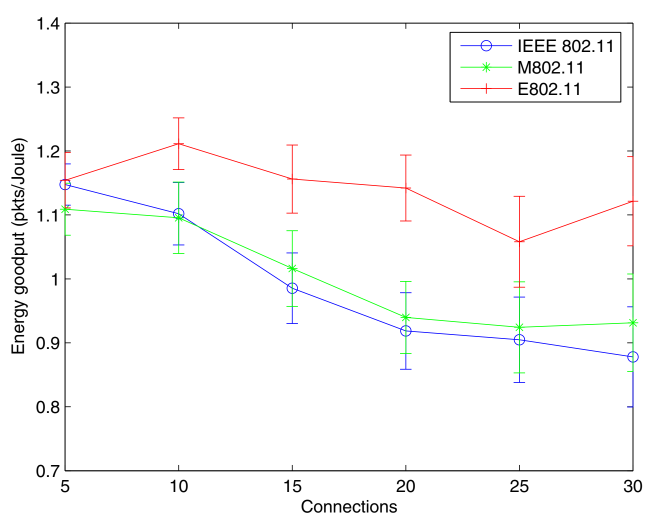

Fig. 5 The number of packets delivered successfully per unit energy vs. the number of connections

From Fig. 6, we see that the E802.11 schemes improves the energy goodput over IEEE 802.11 and M802.11 by approximately from 0.58% to 27.7% and from 4.08% to 20.4%, respectively.

5.2 End-to-end goodput

Figure 7 shows the packet delivery ratio with a 95% confidence interval vs. the number of connections for 802.11, M802.11, and E802.11. From Fig. 7, we see that the packet delivery ratio is about 1 when the traffic load is light (five CBR connections). When the traffic load is moderate to high (10 to 30 CBR connections), the packet delivery ratio becomes lower. In the case that the packet delivery ratio is lower than 1, some packets are queued or discarded somewhere in the network. We further looked into the detailed operations and found that packets are lost at the intermediate (or relay) nodes but not at the sources.

Higher loading at the radio/MAC layer increases the energy and decreases the network performance. From Fig. 7,we know that the packet delivery ratio for E802.11 is much higher than that for 802.11 and M802.11.

In Fig. 7, we note that at five CBR connections, the packet delivery ratio remains independent of the 802.11 and M802.11 or E802.11 because five CBR connections offer light load to the network and the network has enough capacity to handle them. However, the packet delivery ratio does not tell us the real data rate that the network delivered. Instead, the goodput is the appropriate metric for the carried data rate.

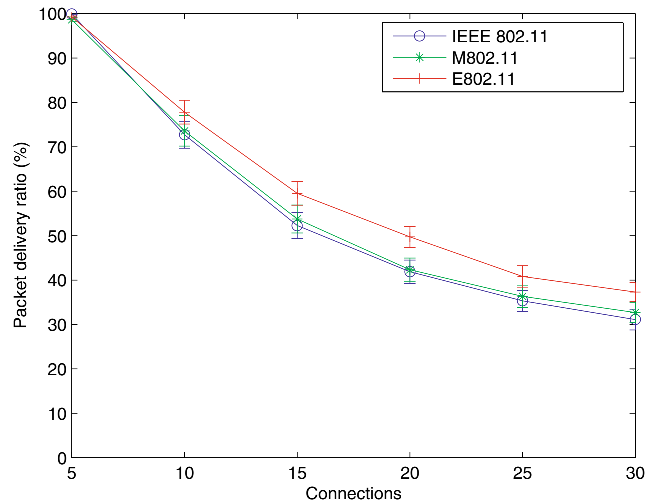

Fig. 7 Packet delivery ratio vs. the number of connections

Figure 8 shows the end-to-end goodput with a 95% confidence interval vs. the number of connections for 802.11, M802.11, and E802.11. And we know that the end-to-end goodput for E802.11 is much higher than that of 802.11 and M802.11. In Fig. 8, as the number of CBR connections increases, the end-to-end goodput also increases. When the number of connections is large, the end-to-end goodput increases. In addition, given a particular CBR connection number, the goodput for E802.11 is still higher than 802.11 and M802.11.

From Fig. 9, we see that the E802.11 schemes improves the end-to-end goodput over IEEE 802.11 and M802.11 by approximately from 7.55% to 20.06% and from 5.92% to 14.06%, respectively.

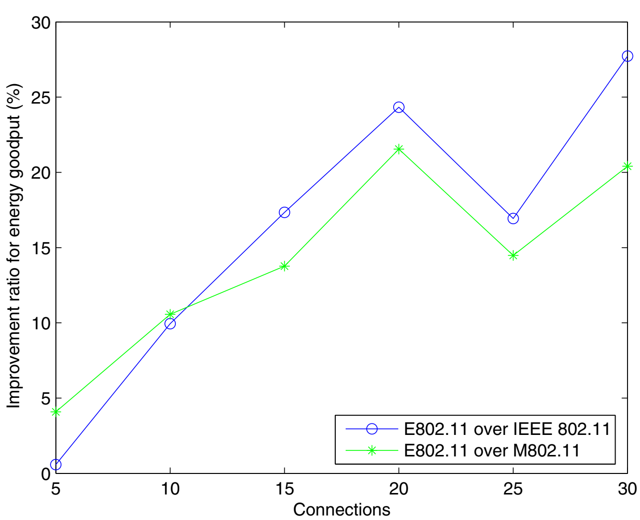

Fig. 6 Improvement ratio for energy goodput vs. the number of connections

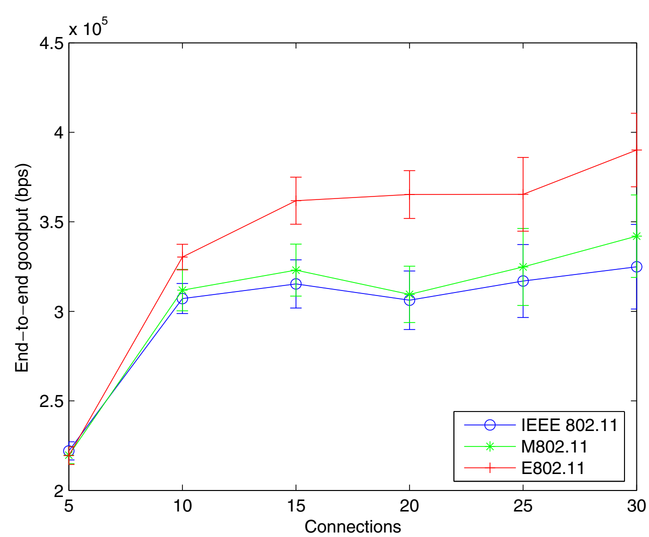

Fig. 8 End-to-end goodput vs. the number of connections

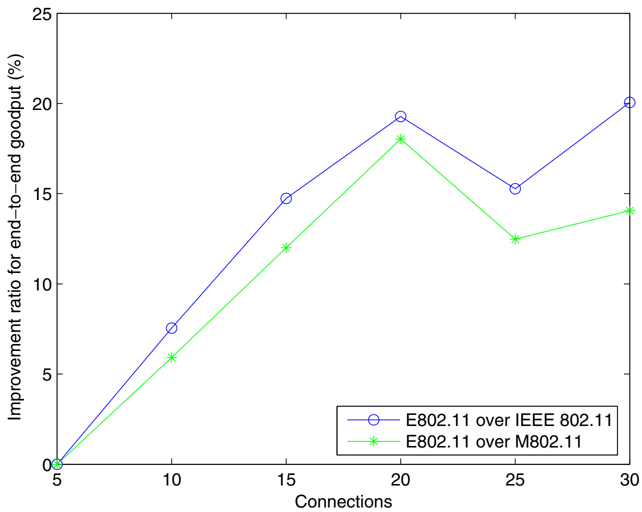

Fig. 9 Improvement ratio for end-to-end goodput vs. the number of connections

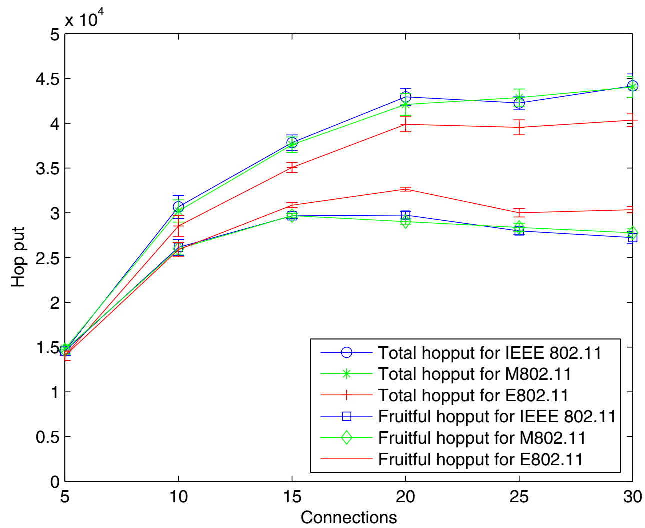

Fig. 10 Total hop-put and fruitful hop-put vs. the number of connections

Take an example from Fig. 4; we know that the average number of hops for a packet that successfully reaches the destination node is about 2.396 at 15 connections for E802.11. From Fig. 8, we know that the end-to-end goodput is about 0.362 Mbps at 15 connections for E802.11. So, we know that the required per-hop throughput should be roughly $2.396 \times 0.362 = 0.867$ Mbps at 15 connections for E802.11. In Fig. 2, we show that the analytical model predicts the per-hop throughput to be around 0.834 to 0.842 Mbps for E802.11. Note that the analytical model considers the saturation throughput. When the traffic load is low, e.g., at five connections, the traffic does not fully utilize the network capacity; therefore, the goodput is lower than that when there are 10 to 30 connections for 802.11, M802.11, and E802.11.

In Fig. 10, we plot hop-puts (number of radio transmissions) vs. the number of connections. Both the fruitful hop-put and the total hop-put are shown. We can see that IEEE 802.11 and M802.11 have a bigger difference in the fruitful hop-put and the total hop-put than E802.11 vs. the number of connections. In other words, more successful radio transmissions in IEEE 802.11 and M802.11 are spent on packets that do not reach their final destinations than E802.11. The reason is that E802.11 has smaller number of congested nodes than IEEE 802.11 and M802.11 at the MAC layer by taking into consideration a node's percentage of residual energy in the design of the backoff mechanism. From Fig. 10, we know that the network in E802.11 wastes lower network resource than IEEE 802.11 and M802.11 and this will improve the packet delivery ratio, end-to-end goodput and end-to-end delay for E802.11.

Figure 11 shows the per-hop throughput vs. the number of connections of simulation and saturation throughput vs. the nodes of analytical model for E802.11. In Fig. 11, the per-hop throughput of simulation equals end-to-end goodput (Fig. 8) multiplied average number of hops (Fig. 4) for a packet that successfully reached the destination node. From Fig. 11, we observe that the saturation throughput for E802.11 from the analytical model is about from 0.834 to 0.842 Mbps. And the per-hop throughput for E802.11 from the simulation is about from 0.774 to 0.918 Mbps when the number of connections is between 10 and 30 in a multihop ad hoc network.

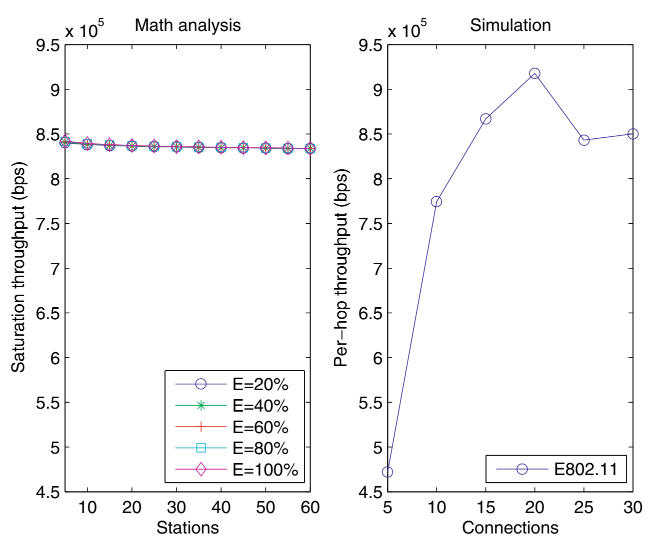

Fig. 11 Comparison of analytical model and simulation for E802.11

5.3 End-to-end delay

In ref. [23], the authors show that the physical transmission delay and routing delay are relatively small and total packet delivery delay is dominated by the MAC delay. The per-hop MAC delay remains about the same regardless of the average number of neighbors. For a multihop network, more hops are required for each packet to reach the destination. Therefore the total delay due to MAC contention is higher for higher loading. For the routing delay, we observe that the per-hop routing delay is higher for larger average numbers of neighbors because the queuing delay is included in the routing delay for each node. For a network with a large average number of neighbors, packets are typically sent to the destination in one or two hops. Therefore there will be more packets queued at the source node or intermediate nodes, and hence longer queuing delay. For a network with a smaller average number of neighbors, queued packets are distributed over the nodes over a longer path; hence each node shares the queuing of the packets and means shorter queuing delay. When summing up all off the per-hop queuing delays, the end-to-end queuing delays for different average number of neighbors are about the same.

In this paper, each node has a nominal radius of 250 m. Therefore, the end-to-end delay per packet or per hop will not be affected by the range of a transmission. The order of delay size is 802.11, M802.11, and E802.11 if we observe the contention window size of each scheme. But in ref. [23], the authors show that the total packet delivery delay is dominated by the MAC delay. In E802.11, we consider the node's percentage of residual energy into the backof /f scheme. Therefore, from Fig. 12, we see that E802.11 is slightly lower than 802.11 and M802.11 for end-to-end delay per packet with a 95% confidence interval in most situations.

From Fig. 13, we see that the E802.11 schemes improves the end-to-end delay per packet over IEEE 802.11 and M802.11 by approximately from 6.18% to 15.88% and from 1.12% to 23.88%, respectively.

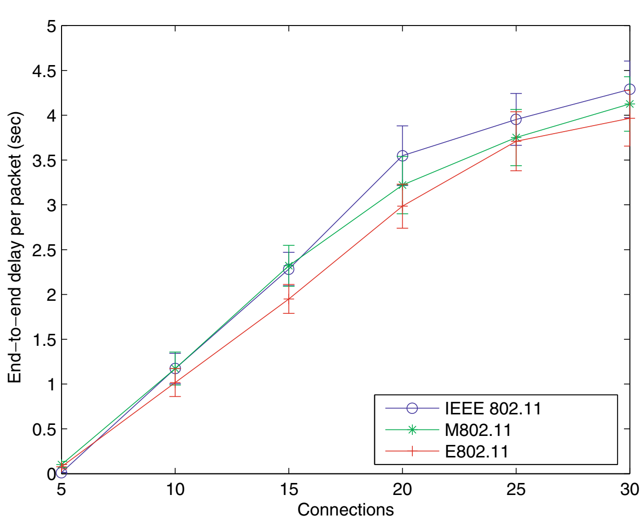

Fig. 12 End-to-end delay per packet (second) vs. the number of connections

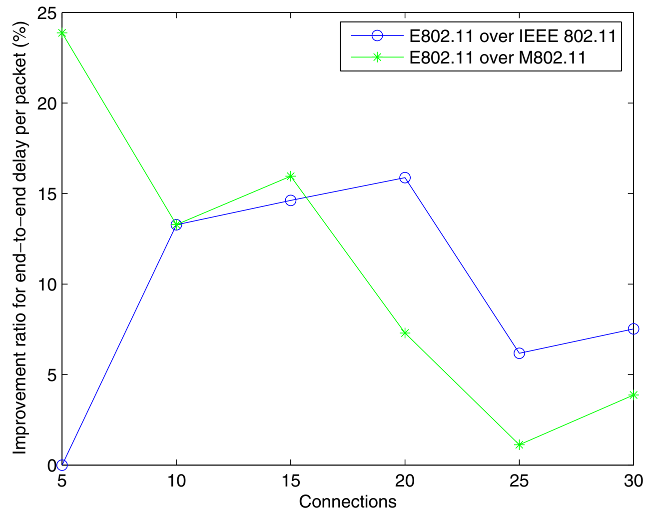

Fig. 13 Improvement ratio for end-to-end delay per packet vs. the number of connections

6 Conclusions

This paper presents an energy-efficient backoff scheme for IEEE 802.11 wireless multihop ad hoc networks. We first analyzed the scheme using a discrete-time Markov chain for wireless multihop ad hoc networks. We observe that the saturation throughput for E802.11 from the analytical model is about from 0.834 to 0.842 Mbps. And the per-hop throughput for E802.11 from the simulation is about from 0.774 to 0.918 Mbps when the number of connections is between 10 and 30 in a multihop ad hoc network. We found that energy-efficient 802.11 achieves better energy goodput by taking into consideration a node's percentage of residual energy in the design of the backoff mechanism. In addition, we consider the node's energy in the backoff scheme; this will decrease the probability of collision in a two-hop contention area and produces higher end-to-end goodput and lower end-to-end delay than IEEE 802.11 and M802.11.

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